GRB Progenitors and their environment

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Abstract. The detection of supernova features in the late spectra of several gamma-ray burst afterglows has shown that at least a fraction of long-duration gamma-ray bursts are associated to the final evolutionary stages of massive stars. Such direct observations are impossible for bursts located at redshift beyond $z \sim 0.5$ and different methods must be used to understand the nature and properties of their progenitors. We review the observational evidence for two particular bursts, for which high quality data are available: GRB 021004 (at $z = 2.323$) and the record redshift GRB 050904 (at $z = 6.29$). We show that both GRBs are likely to be associated to very massive stars, and that in both cases the progenitor stars were able to modify their immediate environments with their radiative and mechanic (wind) luminosity.

Keywords: gamma-ray bursts; Supernovae; HII regions; Mass loss and stellar winds
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INTRODUCTION

The quest to understand the progenitor of Gamma-Ray Bursts (GRBs) has been, and still is, an important branch on the study of these mysterious astronomical objecs. After many years of struggle and observations we now know that at least a fraction of the long duration GRBs are associated to the final evolutionary stages of massive stars and to type Ic supernova (SN) explosions[1, 2, 3, 4, 5].

Even though the association is fairly robust in some cases, all the strong associations are observed in low redshift GRBs, characterized most of the times by lower than usual γ-ray energies. This could well be a selection effect, since SN features can be observed only for small-intermediate redshifts, and low redshift events sample the lower luminosity tail of the luminosity function. Alternative evidence has come about recently, showing that some long duration events are not associated to bright SNe[6, 7, 8]. For the brightest high redshift events the issue is therefore open and indirect indicators must be used to constrain the nature of the progenitors. In addition, even for the bursts with a robustly associated SN, important questions like the properties of the progenitor star, the environment, the metallicity, and the mass loss rate have to be understood.

Traditionally, progenitor indicators are of two classes: the SN hump and the properties of the immediate GRB environment. At very high redshift ($z > 2$), supernova humps become more and more difficult to detect and the investigation of the environment is the most promising method to constrain the progenitor properties. The environment of GRBs can be studied either with absorption studies or by modelling the afterglow emission. Afterglow modelling[9] relies on the spectral and temporal modelling of the afterglow lightcurves to infer density and structure of the ambient medium at a distance of ~ 1 pc from the burster. Even though the technique is in principle very effective, the diversity of afterglows has, especially after the advent of *Swift*[10], made clear that the

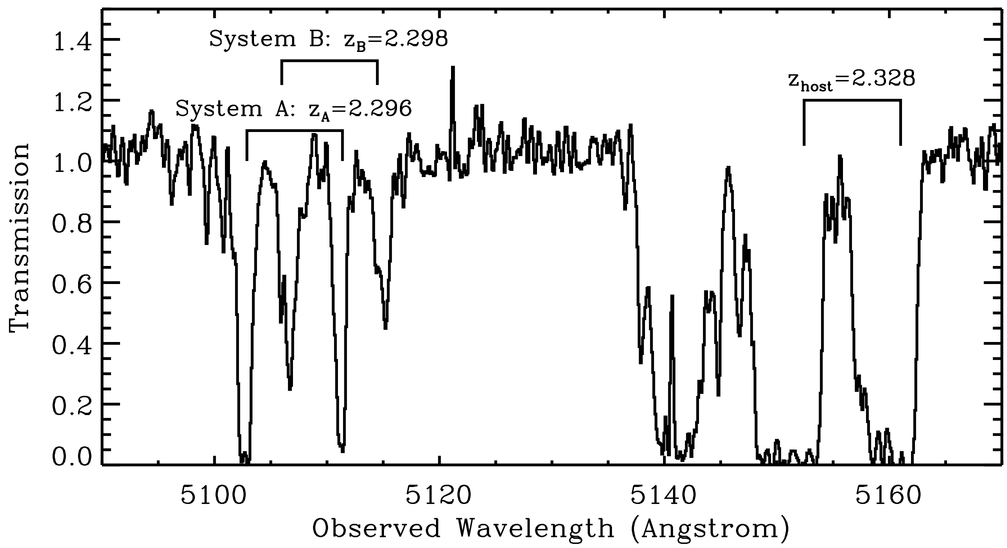

FIGURE 1. A portion of th spectrum of GRB 021004 from the VLT data[20] around the CIV doublet absorption complex.

model is too simple and the results of the modelling either unreliable of dependent on the assumptions made.

The study of absorption continua and features in the optical and X-ray afterglows is potentially a much more powerful probe. Not only it is sensitive to the structure and density structure of the absorber, but can also constrain its metallicity, temperature and dust content. The major problem with absorption measurement is the fact that the distance between the absorber and the light source is unknown. In the case of GRBs, the photon flux within several tens of parsecs from the burster is so large that the status of the absorbing material is modified in a time-dependent way[11, 12]. The effect is generally a reduction of the opacity during the prompt phase and the early afterglow. The system can be completely solved since the speed of the absorption decrement depends on the distance from the burster, while the normalization of the absorption depends on the total amount of absorber present. In practice, a forward fitting method is adopted since the modeled quantity is highly convoluted.

In this review, I concentrate mainly of two events, for which high quality data are available, enabling a thorough modelling of their environments. The first event is GRB 021004, at redshift $z = 2.323$. The second event is GRB 050904, the highest redshift GRB at $z = 6.29$[13, 14].

GRB 021004

Despite the high redshift, GRB 021004 had a very bright afterglow, characterized by high variability on top of the smooth power-law decay[15]. It is, to date, the high redshift afterglow best studied spectroscopically[16, 17, 18, 19, 20, 21]. The observational interest was triggered by the discovery of very high proper motions in the CIV and SiIV

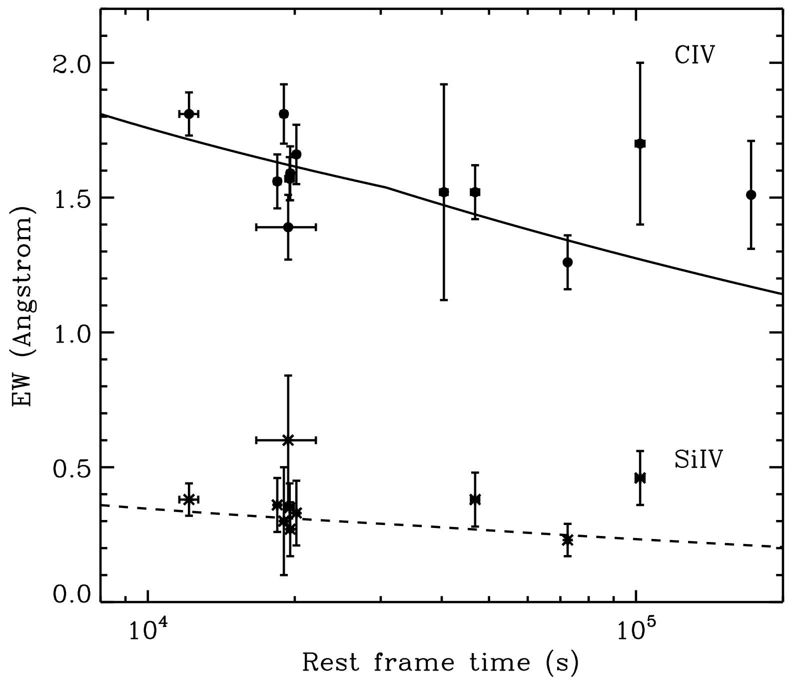

FIGURE 2. Equivalent width of the CIV and SiIV absorption of systems *A* and *B* combined. The lines show the best fit evolution of the lines for absorbing material with a wind distribution out to a radius of ~ 100 pc.

absorption complexes, indicating that material is outflowing from the GRB site towards the observer at speed as large as ~ 3000 km/s[1].

Fig. 1 shows the CIV absorption around the redshift of GRB 021004 in the high-resolution VLT data[20]. Several absorption systems are visible. We consider here the two systems labeled *A* and *B*, since the CIV and SiIV absorptions in the other systems are heavily saturated and therefore it is not possible to measure a reliable column density of the absorbing ions. Twelve measurement of CIV absorption from systems *A* and *B* combined are available, taken at times ranging from 11 hours to ~ 7 days after the event[23]. Analogous measurement, albeit at a lower signal to noise ratio, are available for SiIV. The data show a moderate evidence (about 2σ) of decrease of the equivalent width *EW* in the CIV absorption[23]. Thanks to the availability of high resolution spectroscopy, it is possible to measure the temperature of the absorbers that turns out to be approximately of $\sim 10^6$ K.

The high outflow velocity of the absorber cannot be explained with motions in the galaxy, since those are expected to be one order of magnitude smaller. A likely candidate is the high velocity wind ejected by a Wolf-Rayet star in the WNE or WC phases. Winds are however usually too cold to display strong high-ionization lines. The presence

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[1] The possibility of an intervening system was ruled out by statistical arguments[16, 19]. The discovery of H Lyman α and β absorption associated to the high speed absorption[17] has however put this conclusion under debate, at least for one of the absorption systems[22].

(and possible decay) of CIV absorption therefore allows us to constrain the distance of the absorber. The carbon (and silica) cannot be too close to the burst, or it would be completely ionized by the burst radiation to CV, CVI and CVII. On the other hand, it must be close enough for the photons to convert most of the carbon into CIV. Additional constraints come from the EW variability, which is however marginal for this event.

Figure 2 shows the result of the fitting of a numerical photoionization model[24] on the data[23]. The model assumes that the absorbing material is distributed as a wind with mass loss rate $\dot{M} \sim 2 \times 10^{-4}\ M_{\odot}$/y and with a wind termination radius $R_{\max} > 80$ pc. The metallicity assumed ranges from 100 to 10000 times solar. The distance of the wind termination shock is surprising for at least two reason, but the interpretation is solid as long as the high velocity features are considered local to the GRB (see footnote 1).

First, a wind termination shock so distant implies that the external shock propagated in a stratified medium, while many authors claim the afterglow properties to be consistent with a uniform ISM. In addition, should all GRBs be surrounded by analogous winds, all afterglows should be well described by a wind model, contrary to the results obtained in the modelling[9]. Second, it is very unusual that the wind termination shock lies at such a large distance from the stellar progenitor. This not only requires a very massive progenitor star, but also a very low density environment[25, 26].

Shielding

It has been suggested that a clumpy wind with clumps of approximately $M = 10^{-4} M_{\odot}$ located at ~ 1 pc from the burster would be able to shield the CIV from the burst ionizing photons, allowing for a much smaller termination shock radius[22]. This is not a viable solution. The time integrated prompt emission and early afterglow of GRB 021004 had $N_{\gamma} = 4 \times 10^{60}$ photons. At a distance of 1 pc, this corresponds to a flux of 3.3×10^{22} photons per square centimeter. Since the average photoionization cross-section is approximately 10^{-19} to 10^{-18} cm^2, it can be easily seen that the clumps will be very quickly ionized (each electron "sees" approximately 3000 photons capable of ionizing it).

As a consequence, the shield will be completely ionized in a fraction of a second after the burst onset. By the time the spectroscopic observations are performed, it will be completely transparent, and the ionization of carbon will have expanded out to approximately 100 pc[23]. The proposed shielding effect[22] is not a solution.

GRB 050904

GRB 050904 is a test case to show the potential of modelling the evolution of continuum absorption, in this case in the soft X-rays. This burst was discovered at a very large redshift $z = 6.29$, and was followed with the *Swift* XRT telescope as well as by various optical telescopes. An optical spectrum was obtained with the Subaru telescope[27]. The optical spectrum shows evidence of absorption from SiII local to the GRB host. From the analysis of forbidden line ratios, is was derived that the afterglow photons propagated through a medium with an electron density of several hundreds[27]. Such absorber is

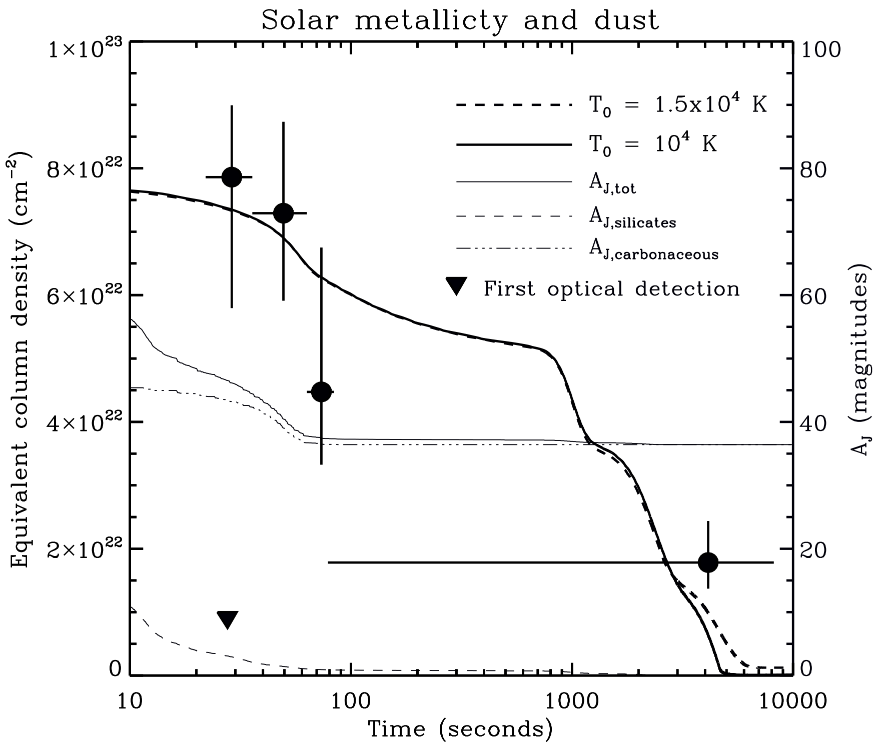

FIGURE 3. Evolution of the equivalent column density measured in the X–ray afterglow of GRB 050904 (dots with errors at $1\,\sigma$). Time is in the rest frame. Solar metallicity with no Fe and Ni has been assumed. The equivalent column density is defined as the column density that would produce the same amount of absorption for a cold non-ionized absorber. The solid and dashed thick lines show the best fit models for different initial temperatures. The photoionization code has in input the observed light curve of GRB 050904. The drop in absorption at $t \sim 1000$ s (in the rest frame) corresponds to the group of bright X–ray flares. The thin lines (and right y axis) show the amount of absorption that would be observed in the J band (rest frame ~ 7.2 eV) if the X-ray absorbing medium would be polluted with Galactic-like dust. The optical transient was observed at $t_{\rm obs} = 200$ s in white light, indicating very little absorption. Thin dashed and dot-dashed lines show the absorption due to silicates only and to carbonaceous grains only, respectively. The little extinction implied by the early optical observation can be explained by a dust component rich in silicates and depleted in carbonaceous grains. This could be the results of an ISM enriched by pair instability SNe.

local to the GRB host galaxy, but must lie at a distance of at least ~ 10 pc from the burster in order for the gas to avoid complete ionization. An analogously high density of the close environment of the GRB is instead inferred from radio observations[28].

Time resolved spectroscopy of the early X-ray afterglow revealed the presence of soft X-ray absorption in excess of the Galactic value. Such excess absorption is not constant but decreases with time[29, 30, 31] as predicted if the absorber lies at close distance to the GRB and is progressively photoionized by the burst photons[12, 32] (see Fig. 3).

The detection of a variable X-ray column allows us to derive two important properties of the absorbing medium. First, the fact that the X-ray column scales almost linearly with metllicity allows us to place a robust lower limit on the metallicity of the GRB environment. If the GRB photons would have propagated through a Thompson thick

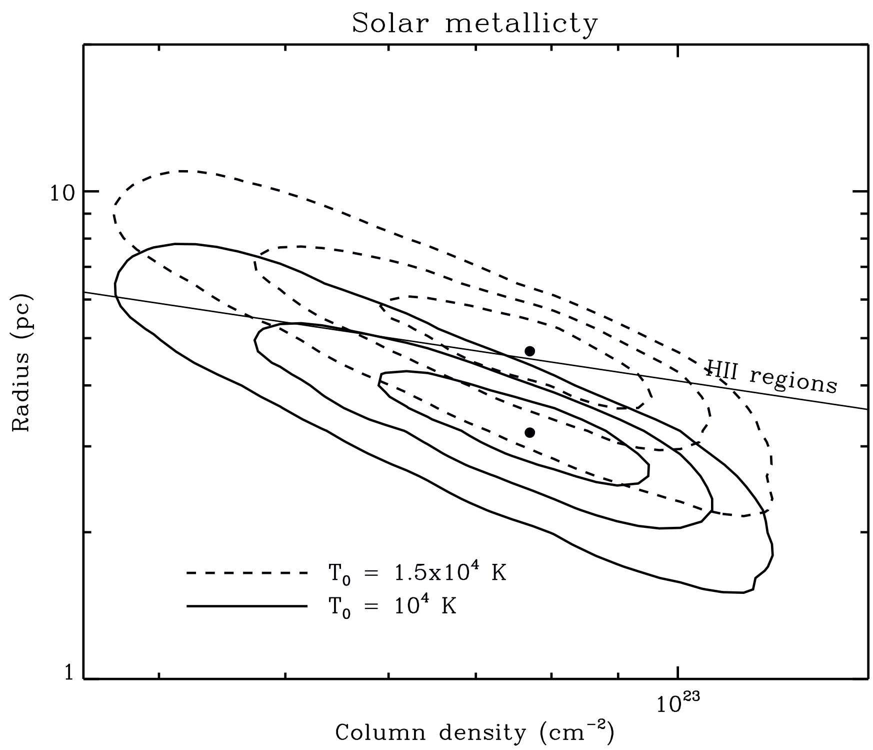

FIGURE 4. Confidence contour (1, 2 and 3-σ) in the radius – column density plane for solar metallicity ISM. The computed grid of radii and column densities over which the fit was performed is much larger, and spans $10^{16} < R < 10^{21}$ cm and $10^{21} < N_H < 10^{25}$ cm^{-2}. The straight line shows the locus of HII regions surrounding massive stars at the end of their life under the assumption of uniform density of the progenitor molecular cloud. Despite the simple model, the agreement is satisfactory.

cloud, they would have been multiply deflected, and the variability pattern would have been smeared out. Since this is not seen in the observations of the GRB prompt emission, it is possible to conclude that the metallicity of the absorber was at least $Z_{\rm absorber} \geq 0.03 Z_\odot$[31].

More detailed constraints can be obtained by modelling the evolution of the observed column density. We used the same time dependent photoionization code described above[24] to model the progressive ionization of metals in the ISM and the sublimation of dust particles. We find that the data can be succesfully reproduced if we assume that the GRB exploded inside a cavity surrounded by a dense shell. The shell lies at several parsecs (see Fig. 4) from the burster and has a total mass of $\sim 10^5$ solar masses[31].

Interestingly, such geometrical properties are expected from an HII region surrounding a massive star born inside a dense molecular cloud (Fig. 4). It is also important to note that due to the total mass of the absorber, it must be preexisting the GRB progenitor. In other words, the absorption cannot be produced by the metals produced by the GRB progenitor. The GRB progenitor was born in a region that had experienced a previous metal enrichment comparable to the solar environment. This is an important constraint for GRB progenitor models, that usually invoke low metallicities in order to reproduce the amount of angular momentum required by the collapsar model[33].

SUMMARY

We have analyzed the environment of two well studied gamma-ray bursts, GRB 021004 and GRB 050904 by means of time dependent spectroscopy. This technique relays on the fact that an absorber located at a distance of ~ 1 to ~ 10 pc from the burster will experience progressive ionization on a timescale of seconds to days. The progressive ionization will be detected observationally as an evolution of the opacity of the medium. Suitable absorption features are resonalnt lines (e.g., CIV and SiIV in GRB 021004) and X-ray lines and continuum (in GRB 050904).

In both the studied events, we find that the environment of the GRB is consistent with that of a very massive star. What differentiates the two cases is that the progenitor star evolved in a low-density environment for GRB 021004, while it evolved in a dense environment in the case of GRB 050904.

It is a dangerous job to draw conclusions based on only two cases. This study seem to suggest that the association of GRBs with massive stars, dramatically proved in low redshift cases, holds up to very high redshifts. More cases with high quality data have to be investigated before we can say a final word. We showed that the analysis of time resolved spectroscopy is a very robust mean of exploring the GRB environment.

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